



Aerodynamic Optimization of a Cruise-Slotted Transonic Truss-Braced-Wing Aircraft Configuration

Timothy Chau*, Michael G. Piotrowski**, and
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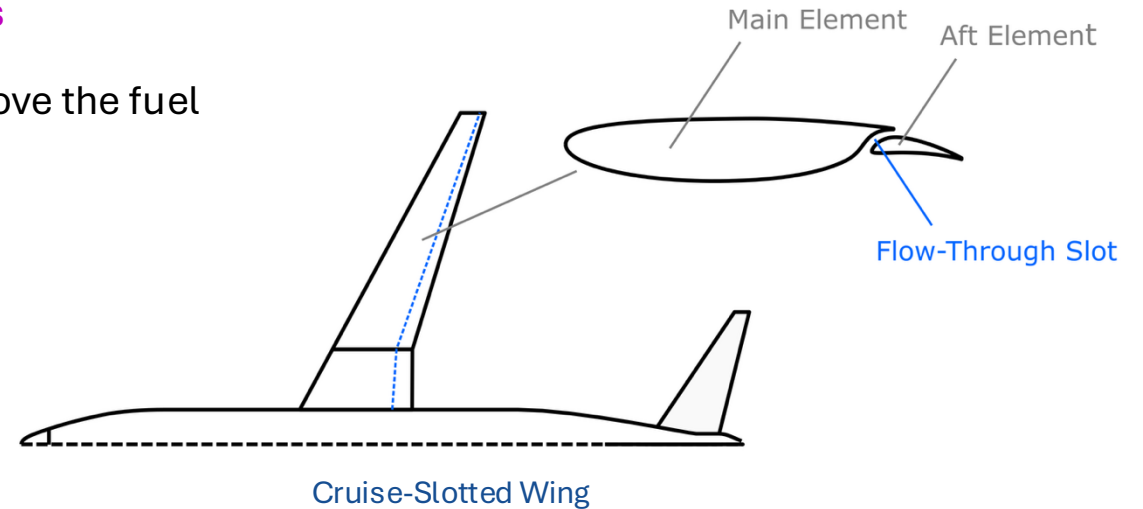
Computational Aerosciences Branch
NASA Ames Research Center

NASA Advanced Modeling & Simulation (AMS) Seminar Series
NASA Ames Research Center
February 25, 2026

Motivation



- Demand for air travel is projected to **double in the next 15 years**
- Major advances in air transport technology are needed to improve the fuel efficiency of commercial transport aircraft
 - Reduced operating costs for airlines
 - Increased market competitiveness of future aircraft
- Two promising aircraft technologies:
 1. **Cruise-slotted wing^{1,2}**
 2. **Transonic truss-braced-wing (TTBW) configuration**



Transonic Truss-Braced Wing (Image Credits: NASA)



Sustainable Flight Demonstrator (Image Credits: NASA/Boeing)

¹Whitcomb and Clark, 1965. NASA TM X-1109 ²Vassberg et al. 2006. US Patent 7,048,228

The Cruise-Slotted Wing (CSW)

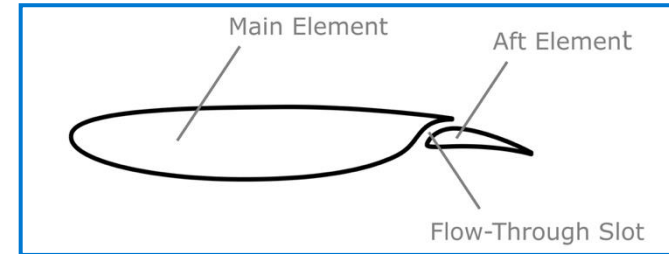


Advantages:

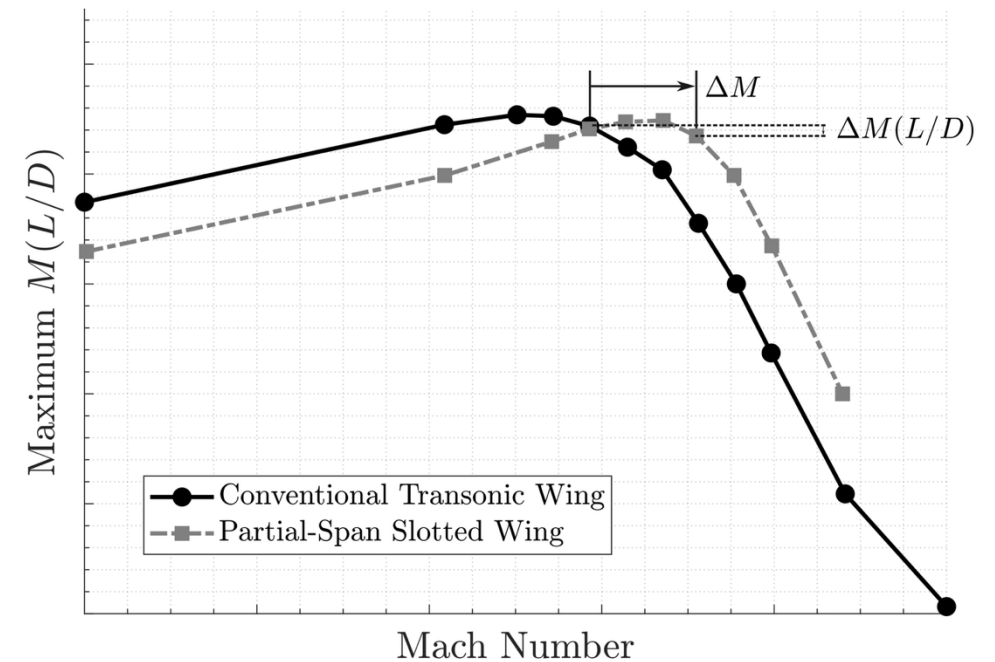
- Increased aerodynamic loading with delayed boundary-layer separation
- Reduced wave drag through increased drag divergence Mach number
 - Conceptually modeled as an increase to airfoil technology factor in the Korn equation
- Higher cruise Mach numbers for similar aerodynamic range efficiency
- Natural laminar flow from more gradual main-element pressure gradients, enabled by aggressive pressure recoveries

Aerodynamic Design Challenges:

- Increased skin-friction drag penalties from wetted area, higher speed slot flow, and newly-formed boundary layer on aft element



Notional slotted airfoil



Wind tunnel data adapted from Vassberg et al. 2006 (US Patent 7,048,228)

The cruise-slotted wing topology can delay shock-induced boundary layer separation, enabling aircraft operation at increased speeds for small penalties in maximum aerodynamic range efficiency, $M(L/D)$.

The Transonic Truss-Braced Wing (TTBW)

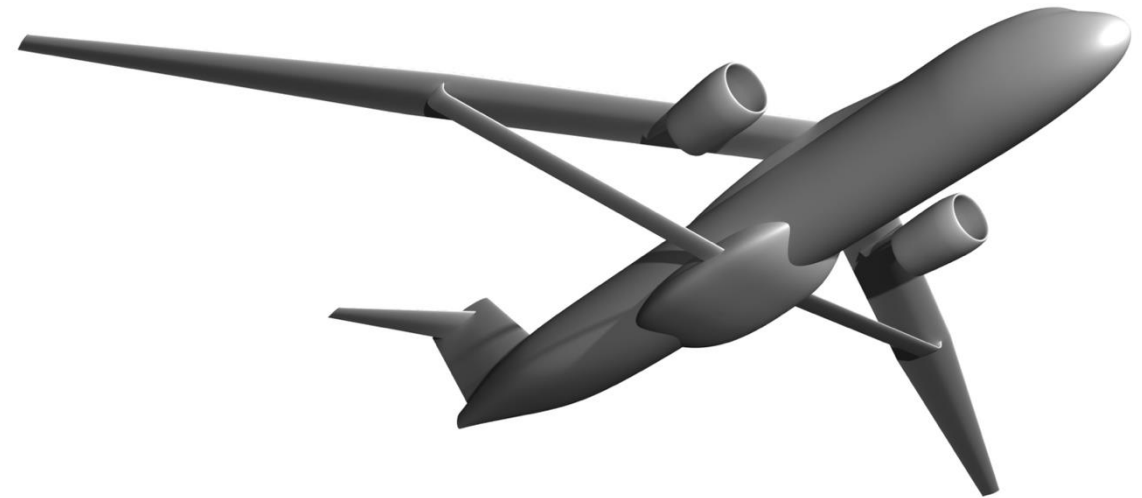


Advantages:

- **Significantly lower induced drag** due to larger wing span (+25-50%)
- **Higher structural efficiency** due to truss topology
 - Supports higher wing bending loads
 - Enables thinner wings
 - Lowers structural weight
- **Natural laminar flow** from reduced Reynolds numbers

Aerodynamic Design Challenges:

- **Shock formation in truss region** due to flow acceleration in small enclosed space(s) at transonic speeds
- **Flow interference + skin-friction drag penalties** from strut members



Notional transonic truss-braced-wing aircraft

How do we address these aerodynamic design challenges?

Aerodynamic Shape Optimization



- Aerodynamic shape optimization automates the design process through specified objective functions, design variables, and constraints, *avoiding the need for extensive a priori design experience*
- Aerodynamic shape optimization based on the **Reynolds-averaged Navier-Stokes (RANS)** equations:
 - Captures shock formation, boundary-layer separation, and nonlinear interference
 - Accurately captures and enables tradeoffs between induced drag, viscous drag, and wave drag

$$M = 0.78, Re = 20 \times 10^6$$

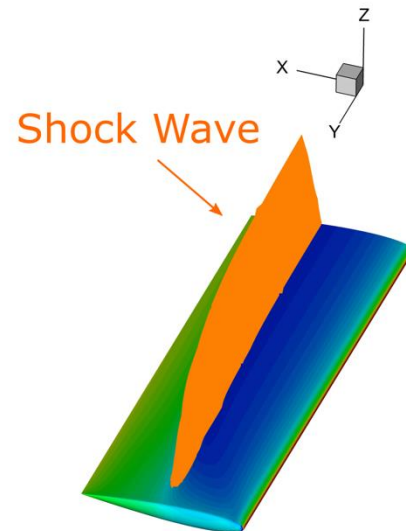
Initial

$$\alpha = 1.00^\circ$$

$$L/D = 8.7$$

$$C_L = 0.09$$

$$C_D = 0.0107$$



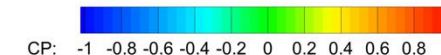
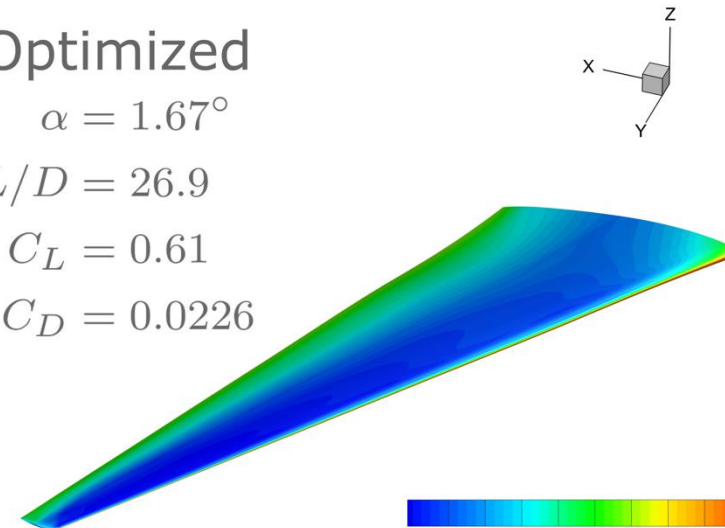
Optimized

$$\alpha = 1.67^\circ$$

$$L/D = 26.9$$

$$C_L = 0.61$$

$$C_D = 0.0226$$

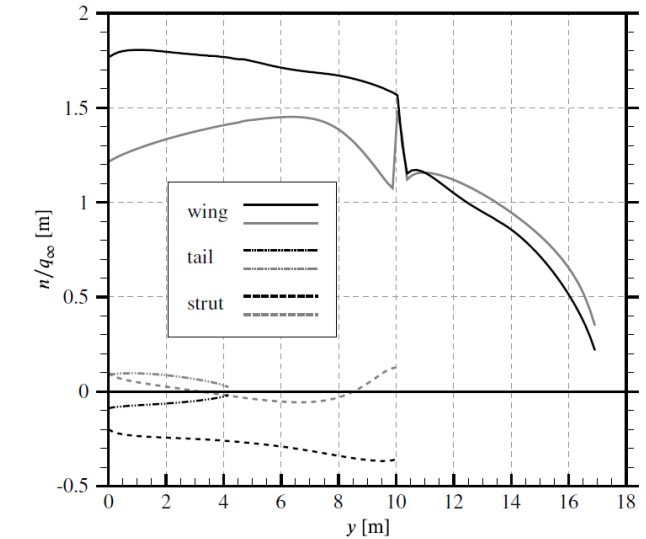
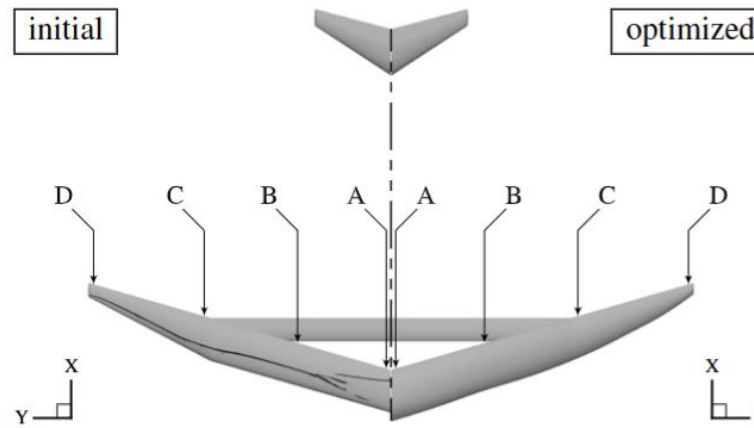


Previous Aerodynamics Research on TTBW (1/2)

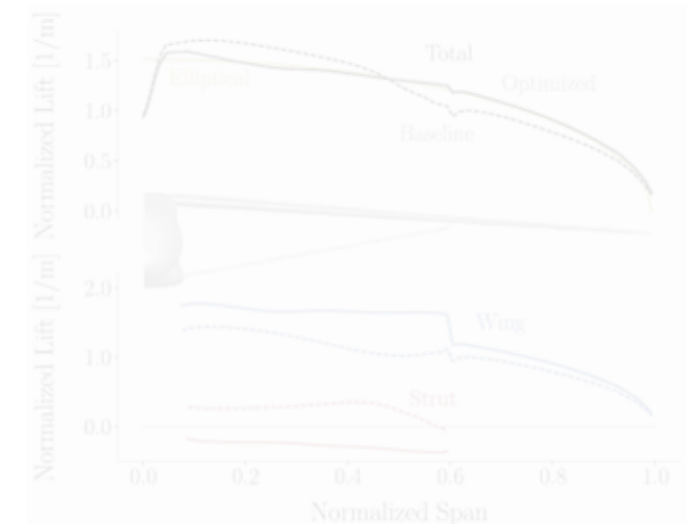
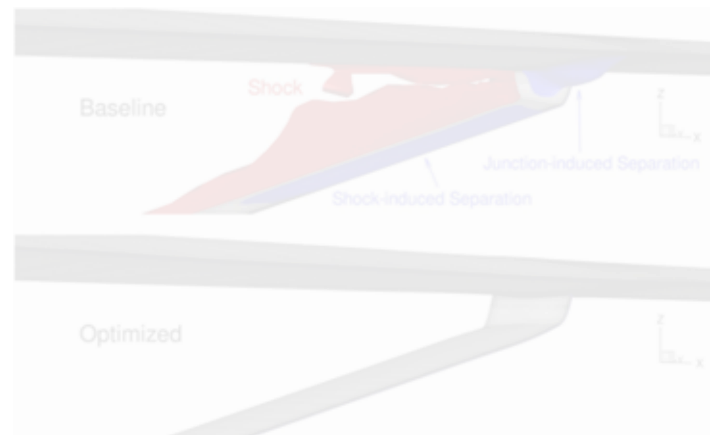


- **Gagnon and Zingg (JoA 2016):**

- Mach 0.78, $C_L \sim 0.500$ regional jet truss-braced wing
- Single-point Euler-based optimization (inviscid)
- 40.3% less cruise pressure drag than equivalent conventional tube-and-wing



Gagnon and Zingg (2016)



Secco and Martins (2019)

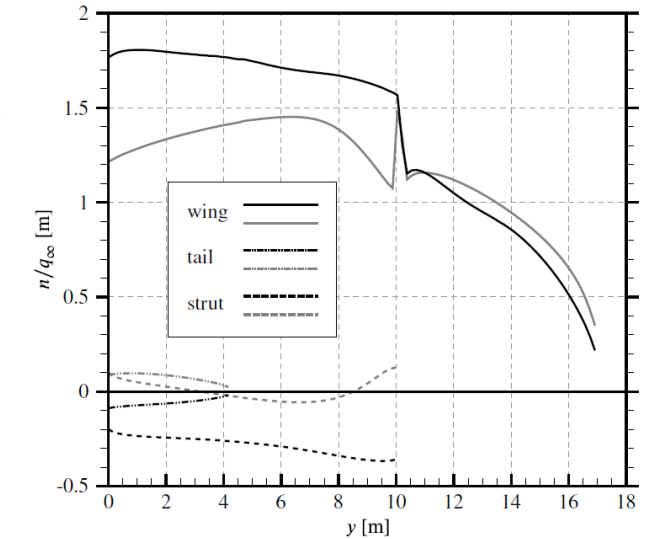
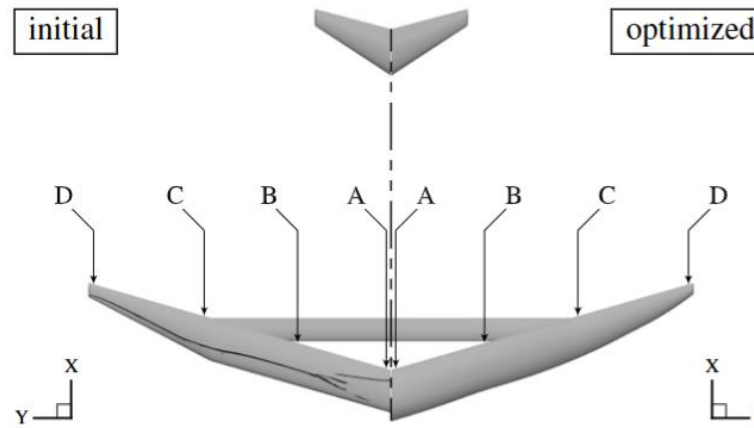
¹Gagnon and Zingg, *Journal of Aircraft*, 2016. doi: 10.2514/1.C033591

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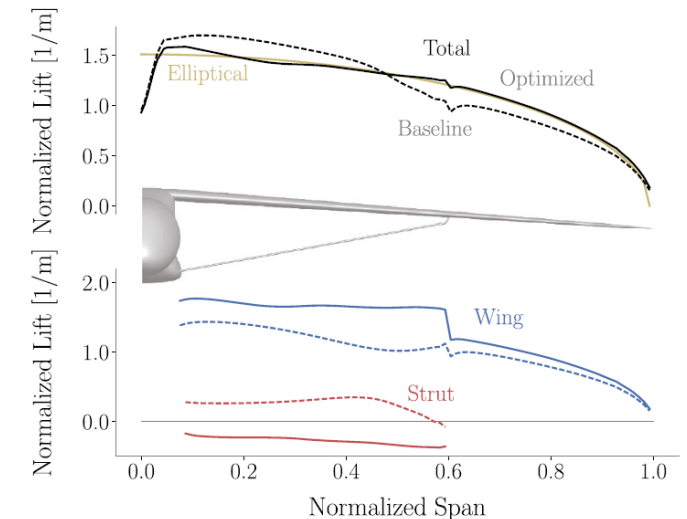
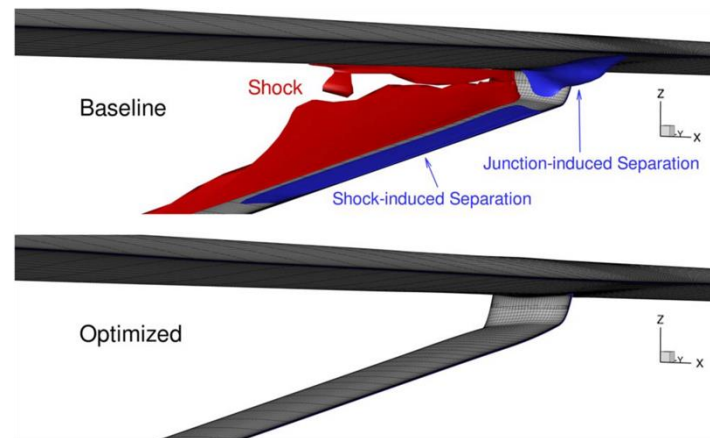
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- 40.3% less cruise pressure drag than equivalent conventional tube-and-wing



Gagnon and Zingg (2016)

- **Secco and Martins (JoA 2019):**

- Mach 0.72, $C_L \sim 0.406$ single-aisle PADRI geometry
- Single-point RANS-based optimization
- Mitigated wing-strut-junction shock formation and boundary-layer separation



Secco and Martins (2019)

¹Gagnon and Zingg, *Journal of Aircraft*, 2016. doi: 10.2514/1.C033591

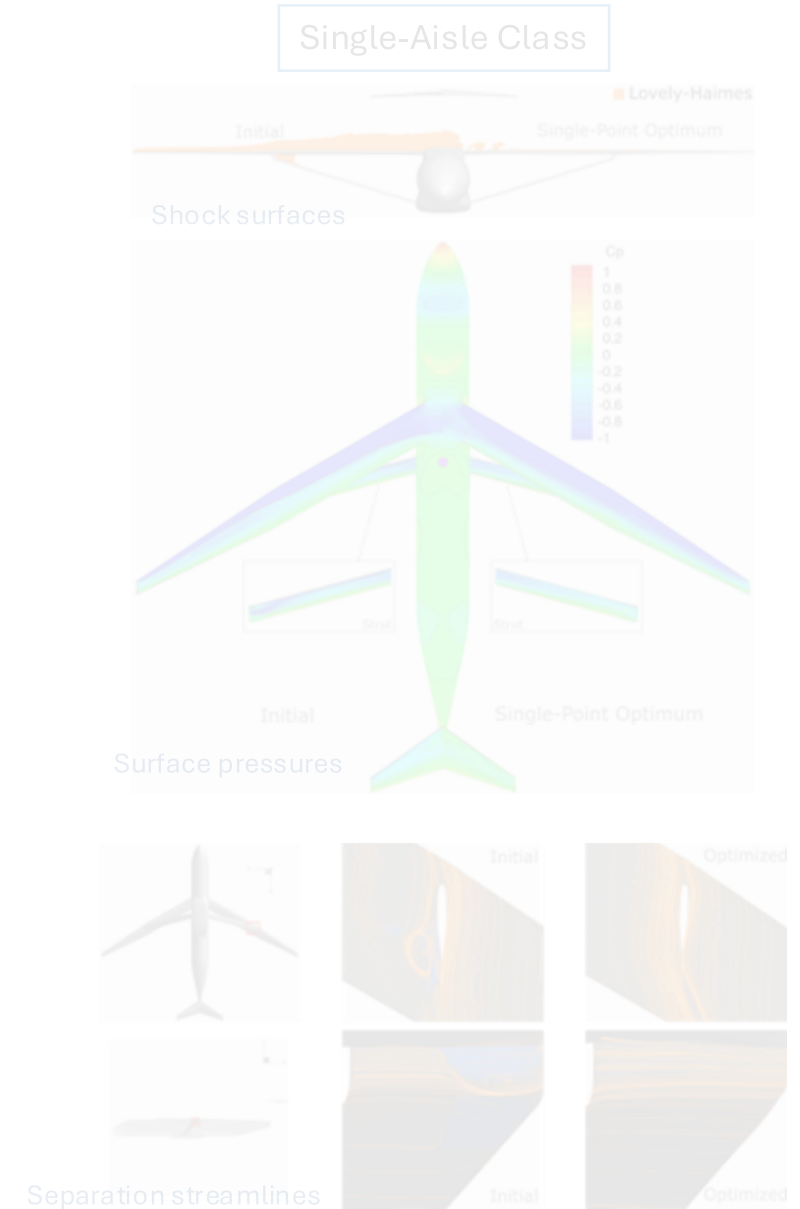
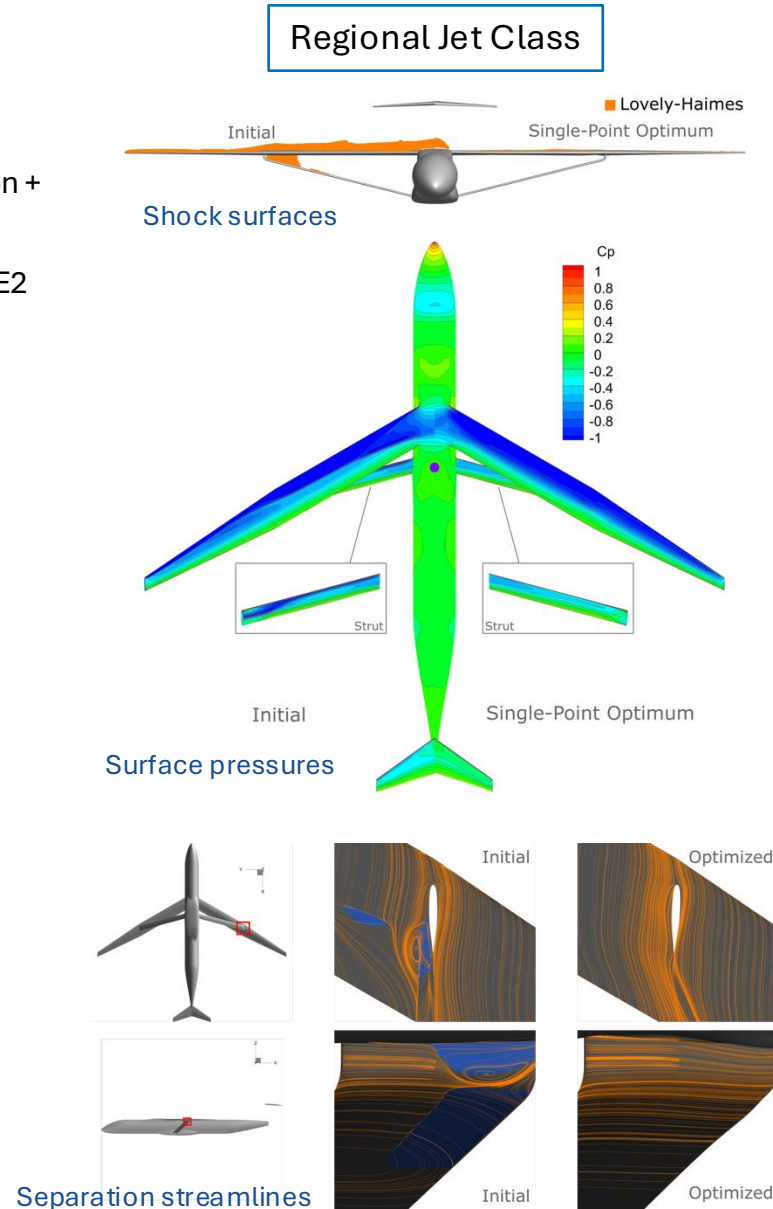
²Secco and Martins, *Journal of Aircraft*, 2019. doi: 10.2514/1.C034934

Previous Aerodynamics Research on TTBWs (2/2)



- **Chau and Zingg (JoA 2022, AJ 2022):**

- Mach 0.78, C_L 0.682 regional jet TTBW aircraft
- Single- and multipoint RANS-based optimization + systems analysis
- ~13% higher cruise lift-to-drag ratio than E190-E2
- 7.6–7.8% less fuel burn (block) than E190-E2



¹Chau and Zingg, *Journal of Aircraft*, 2022. doi: 10.2514/1.C036389

²Chau and Zingg, *The Aeronautical Journal*, 2022. doi: 10.1017/aer.2022.64

Previous Aerodynamics Research on TTBWs (2/2)



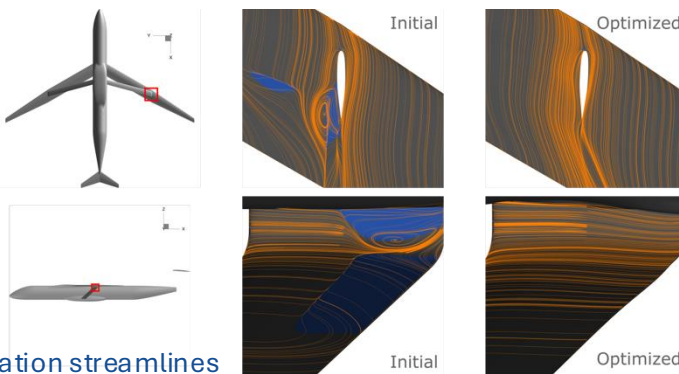
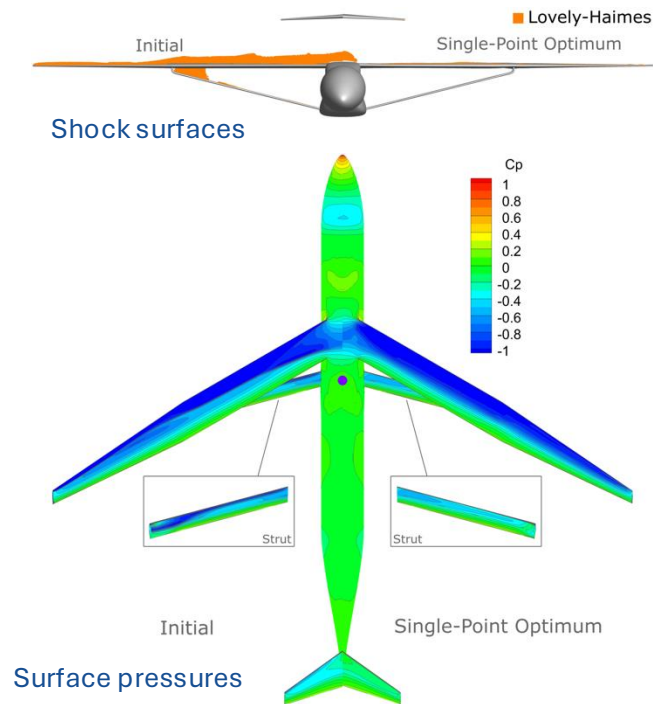
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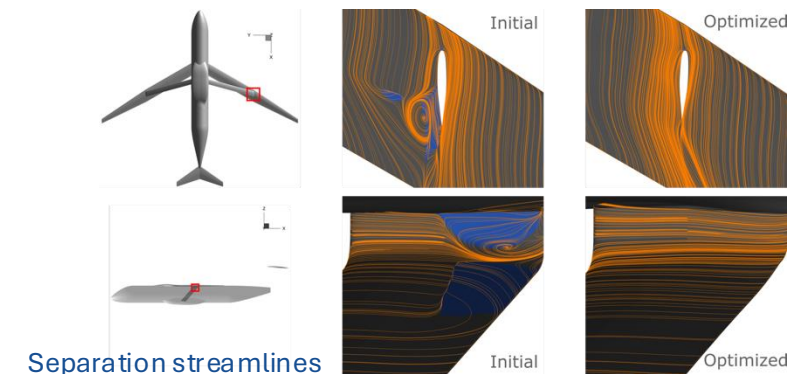
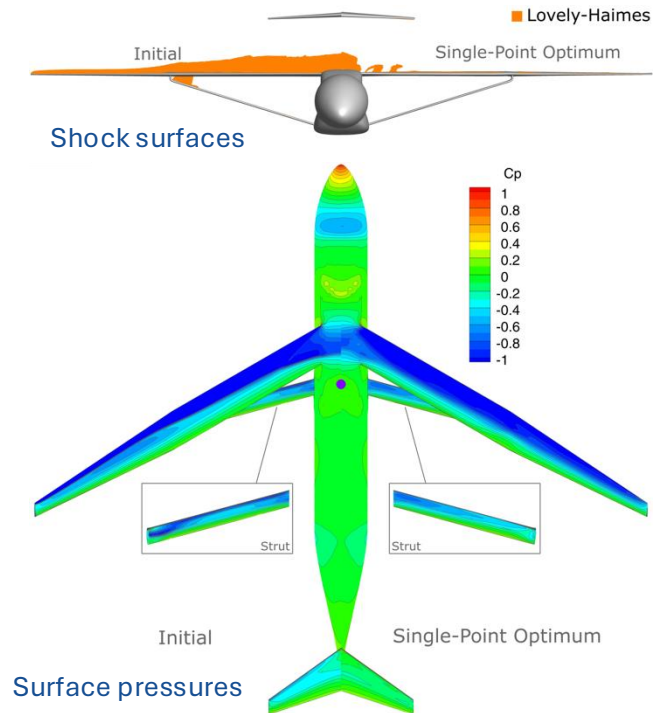
- **Chau and Zingg (JoA 2023):**

- Mach 0.78, C_L 0.750 single-aisle TTBW aircraft
- Single- and multipoint RANS-based optimization + systems analysis
- 12–13% higher cruise lift-to-drag ratio than A320neo
- 7.8–8.2% less fuel burn (block) than A320neo

Regional Jet Class



Single-Aisle Class



¹Chau and Zingg, *Journal of Aircraft*, 2022. doi: 10.2514/1.C036389

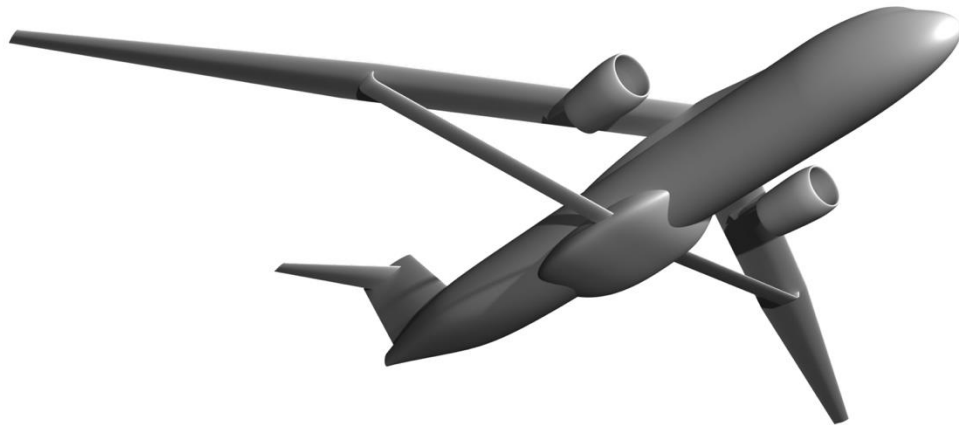
²Chau and Zingg, *The Aeronautical Journal*, 2022. doi: 10.1017/aer.2022.64

³Chau and Zingg, *Journal of Aircraft*, 2023. doi: 10.2514/1.C037158

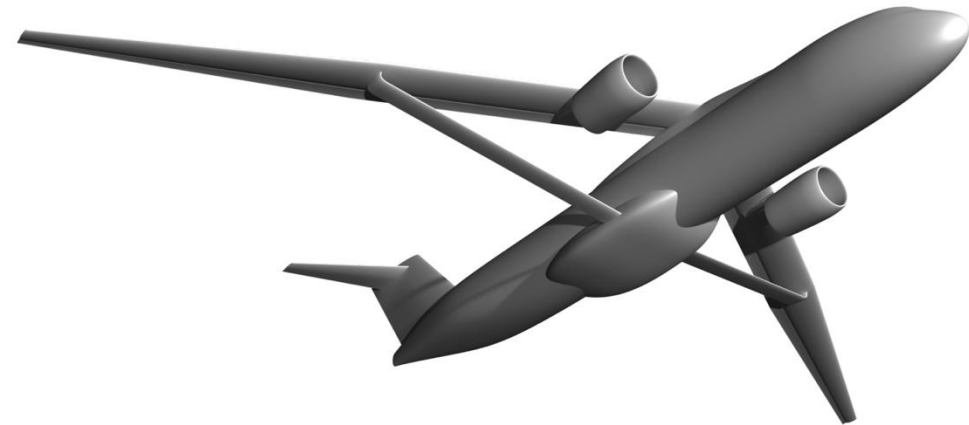
Objectives



1. Investigate the aerodynamic design of a single-aisle cruise-slotted transonic truss-braced-wing (TTBW) aircraft configuration through the application of aerodynamic shape optimization based on the Reynolds-averaged Navier-Stokes (RANS) equations
2. Evaluate the aerodynamic performance of the cruise-slotted TTBW aircraft configuration
 - Comparisons to an equivalently optimized non-slotted TTBW configuration
 - Mach number sensitivity studies to compare drag rise and aerodynamic range efficiency curves, i.e., C_D vs. Mach number and $M(L/D)$ vs. Mach number



Notional non-slotted TTBW aircraft.



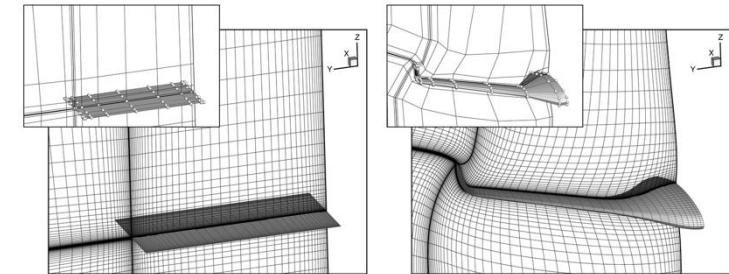
Notional cruise-slotted TTBW aircraft.

Jetstream: Aerodynamic Shape Optimization Framework



Mesh Parameterization and Deformation¹, and Geometry Control²

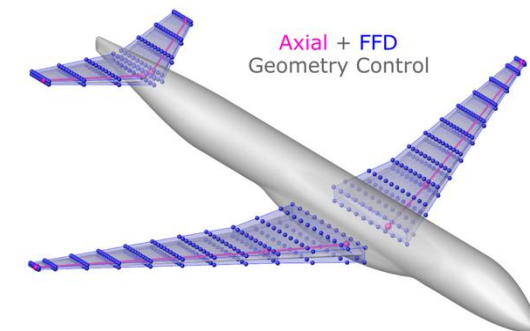
- B-spline volume parameterization
- Linear elasticity model for deforming B-spline volumes
- Axial and free-form deformation method



Mesh Parameterization and Deformation

Structured Multiblock Flow Solver³

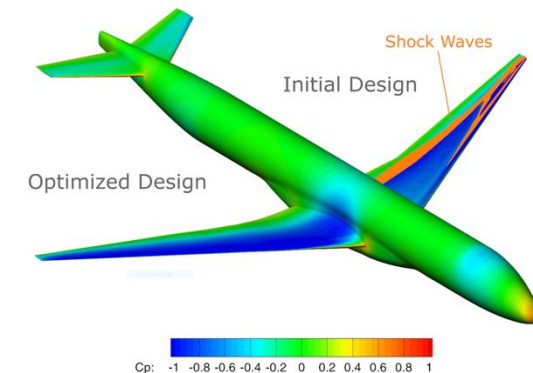
- Reynolds-averaged Navier-Stokes (RANS) equations fully-coupled with the Spalart-Allmaras (SA) turbulence; includes QCR2000
- Parallel implicit Newton-Krylov-Schur method



Optimization and Gradient Evaluation⁴

- SNOPT for gradient-based optimization
- Large-scale linear and nonlinear constrained problems
- Discrete adjoint method, analytical, complex step method

- ❖ Post-optimization grid-refinement studies performed with LAVA Curvilinear⁵, a RANS-based flow solver similar to Jetstream's that can use structured overset meshes



¹Hicken and Zingg, *AIAA Journal*, 2010. doi: 10.2514/1.44033

²Gagnon and Zingg, *AIAA Journal*, 2015. doi: 10.2514/1.J053575

³Osusky, M. and Zingg, *AIAA Journal*, 2013. doi: 10.2514/1.J052487

⁴Osusky, L. et al., *AIAA Journal*, 2015. doi: 10.2514/1.J053457

⁵Kiris et al., *AST*, 2016. doi: 10.1016/j.ast.2016.05.008

Reference Aircraft Concept and Design Conditions

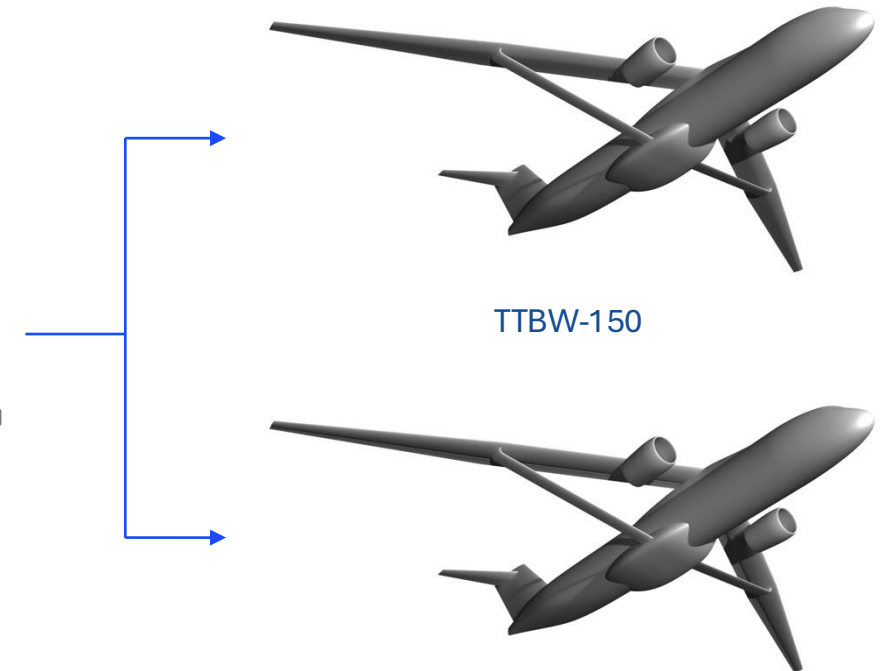


- **Reference concept:** Single-aisle, 154-passenger transonic truss-braced-wing (TTBW) transport aircraft developed based on the Mach 0.80, high-sweep variant of the Boeing SUGAR High¹
- Cruise-slotted variant introduces a full-span slotted wing (proof of concept)
- Aerodynamic shape optimization at economy range mission cruise conditions: $M = 0.80$, $C_L = 0.560$, and $Re = 12.12$ million

Parameter	Value
Mean aerodynamic chord, ft	9.17
Wing area (gross), sq-ft	1,467
Wing span, ft	170
Wing sweep (mid chord), deg	30.0
Maximum payload, lb	46,000
Design payload, lb	30,800
Design range, nmi	3,500
Economy range, nmi	900



Reference TTBW aircraft concept



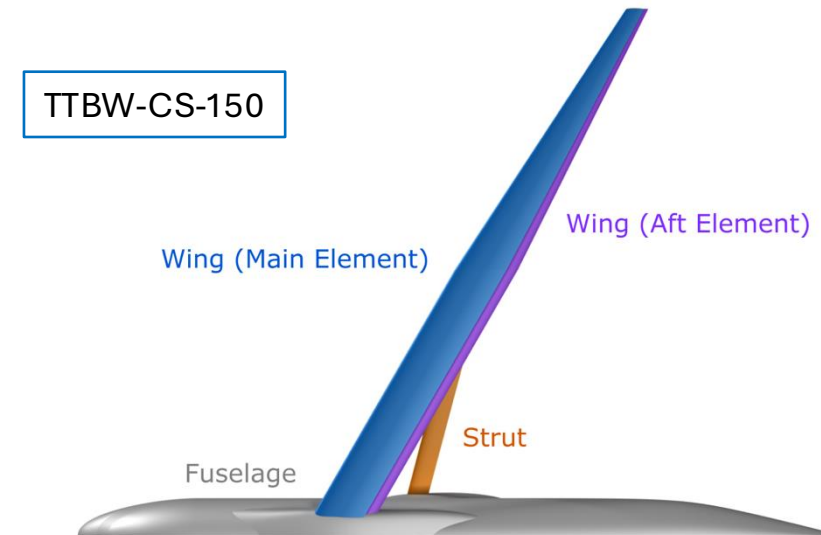
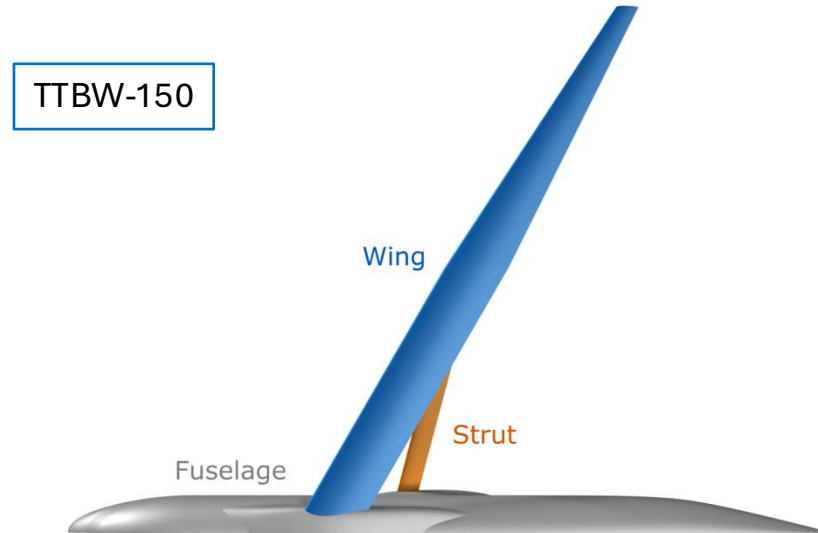
TTBW-CS-150

¹Bradley, Droney, and Allen, 2015, NASA/CR-2015-218704/Volume I

Baseline Geometries



- 3D models consist of wing, strut, and fuselage only
- **Baseline wing**
 - **TTBW-150:** defined by RAE-2822 airfoils
 - **TTBW-CS-150:** defined by Whitcomb slotted airfoils (full span)
- **Baseline strut** defined by NASA SC(2)-0012 supercritical symmetric airfoils
- **Baseline fuselage** based on B737-8, with wing and strut fairings based on publicly-released PADRI workshop¹ geometry



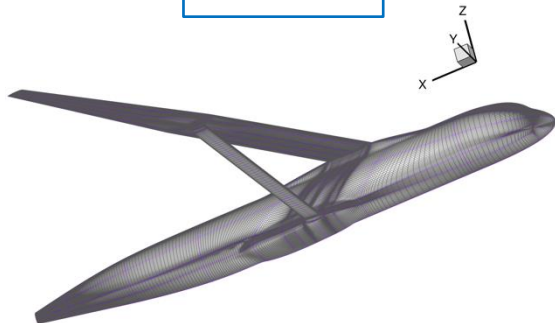
¹<https://www.acare4europe.org/sria>

Optimization and Post-Optimization Analysis Grids

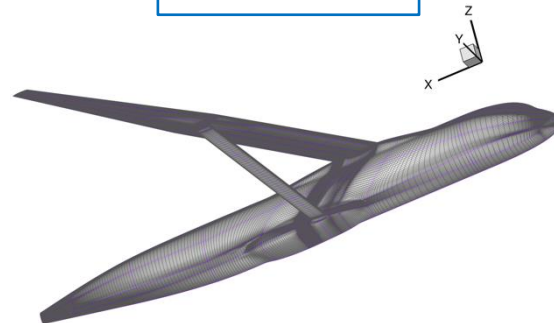


Solver/Framework	Type	Grid Level	Num. of Blocks	Refinement Factor	Num. of Nodes (M)	Average y^+
TTBW-150						
Jetstream	Struct. Multiblock	L0	898	--	18.25	0.494
LAVA	Struct. Overset	L0	--	1.00	33.10	0.937
LAVA	Struct. Overset	L1	--	1.26	64.78	0.684
LAVA	Struct. Overset	L2	--	1.59	130.54	0.560
TTBW-CS-150						
Jetstream	Struct. Multiblock	L0	1,406	--	22.65	0.511
LAVA	Struct. Overset	L0	--	1.00	35.67	0.938
LAVA	Struct. Overset	L1	--	1.26	69.58	0.676
LAVA	Struct. Overset	L2	--	1.59	140.33	0.568

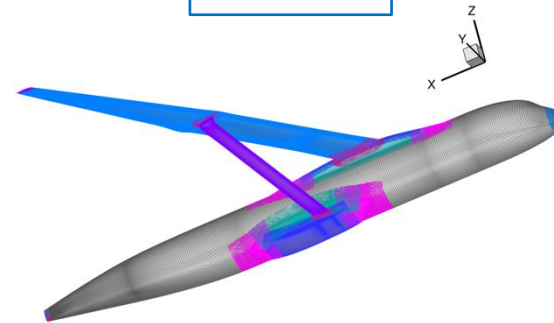
TTBW-150



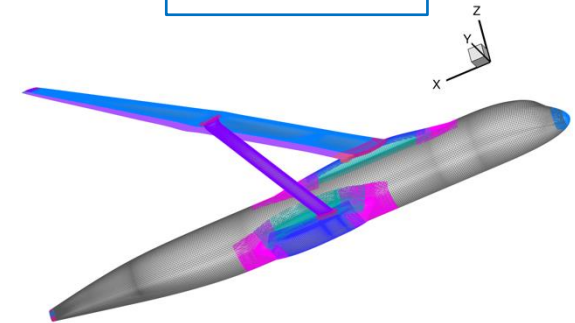
TTBW-CS-150



TTBW-150



TTBW-CS-150



Structured multiblock grids used for aerodynamic shape optimization (L0 surface meshes/patch topologies shown).

Structured overset grids used for post-optimization grid-convergence studies (L0 surface meshes/patch topologies shown).

Optimization Problem Formulation



Objective (1):

minimize Drag (1)

Design Variables (942):

w.r.t. Angle of attack (1)

Twist (39)

Section shape (902)

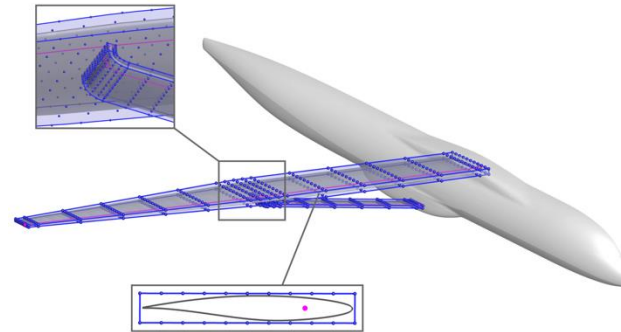
Nonlinear Constraints (32):

s.t. Constant lift (1)

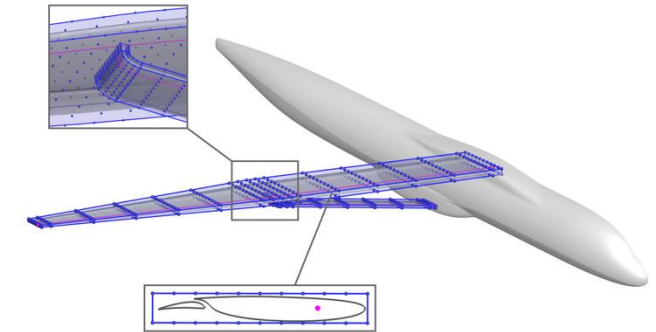
Minimum wing and strut volume (1)

Minimum $(t/c)_{\max}$ (30)

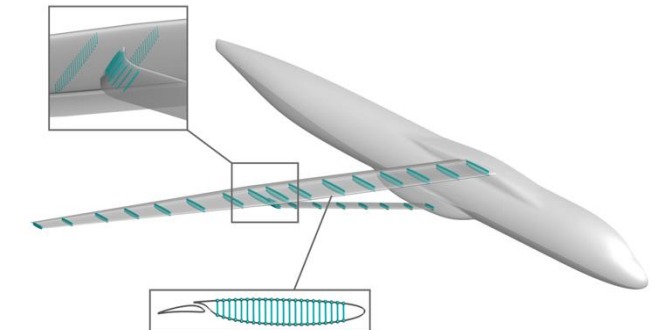
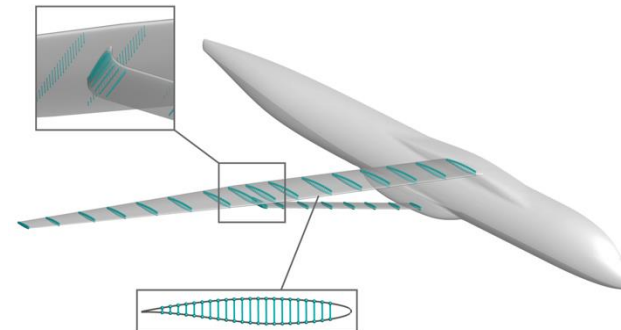
TTBW-150



TTBW-CS-150



Geometry control systems consisting of **axial curves** and **free-form deformation (FFD) volumes**.



Line probes defining the sectional **minimum $(t/c)_{\max}$ constraints**.

The optimization problems are consistent between the TTBW-150 and TTBW-CS-150 aircraft configurations.

TTBW-150: Overall Design and Flow Features



Flow Conditions

$$M = 0.80$$

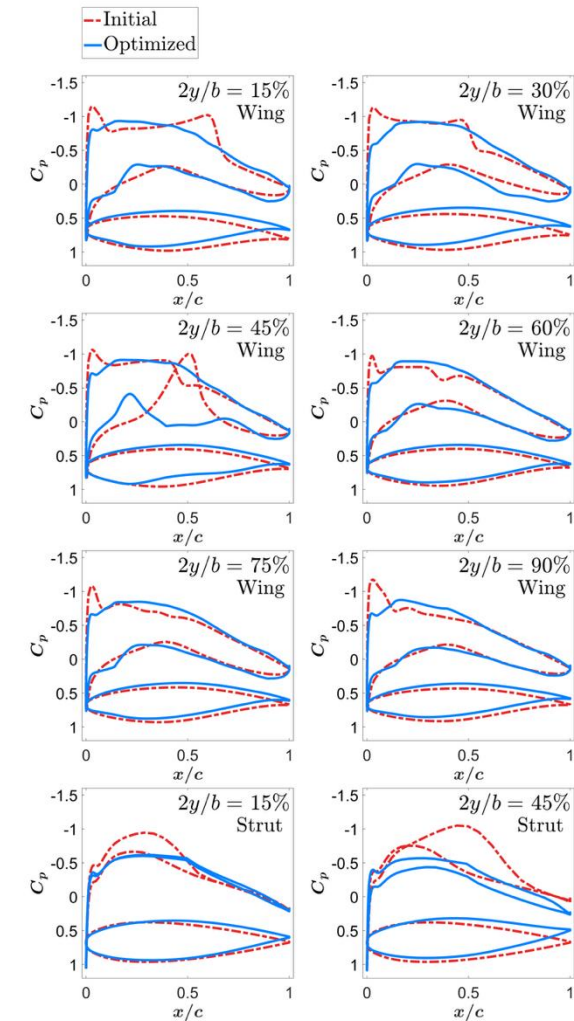
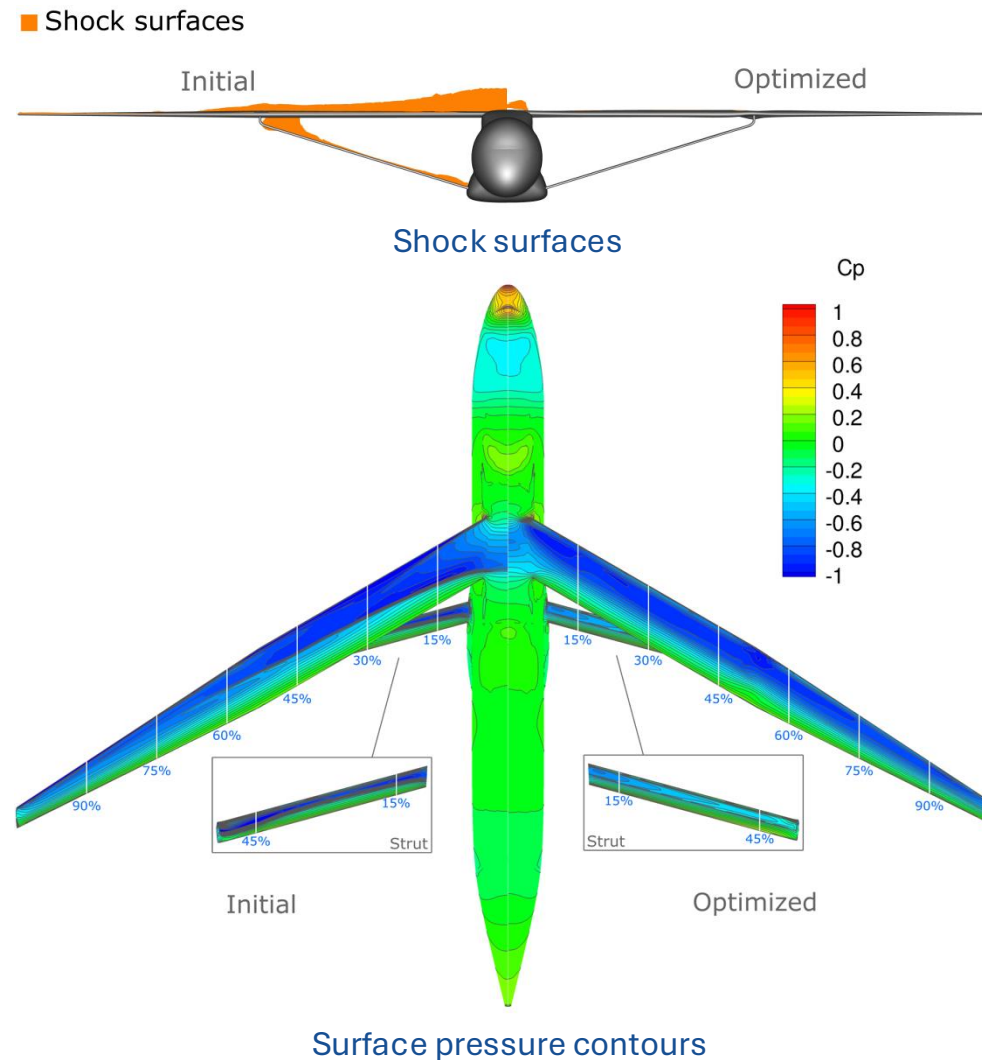
$$Re = 12.12 M$$

Optimized Aerodynamic Performance

$$C_L = 0.560$$

$$C_D = 0.0216$$

$$L/D = 25.9$$



Airfoil profiles and pressure distributions

Optimization successfully mitigates shock formation in and around the wing-strut junction. Optimized pressure distributions feature smooth pressure recoveries, typical of RANS-based aerodynamic shape optimization.

TTBW-CS-150: Overall Design and Flow Features



Shock surfaces



Flow Conditions

$$M = 0.80$$

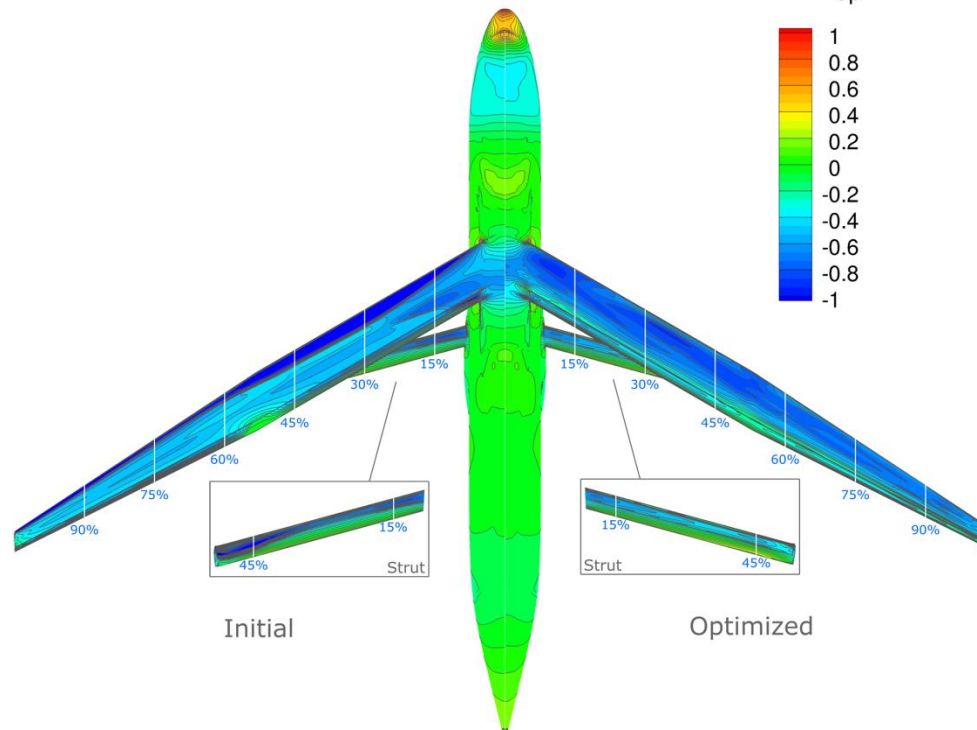
$$Re = 12.12 M$$

Optimized Aerodynamic
Performance

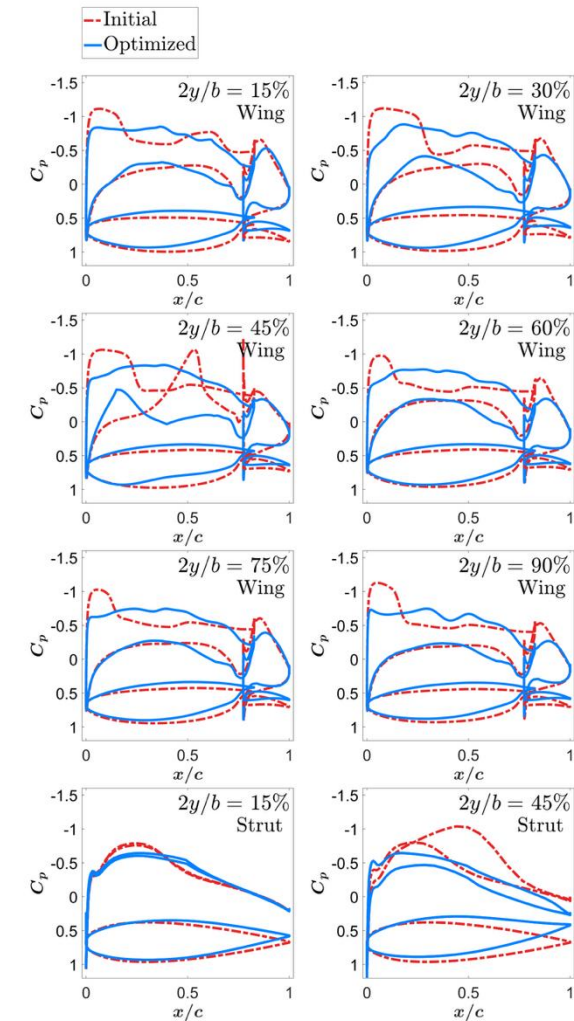
$$C_L = 0.560$$

$$C_D = 0.0223$$

$$L/D = 25.2$$



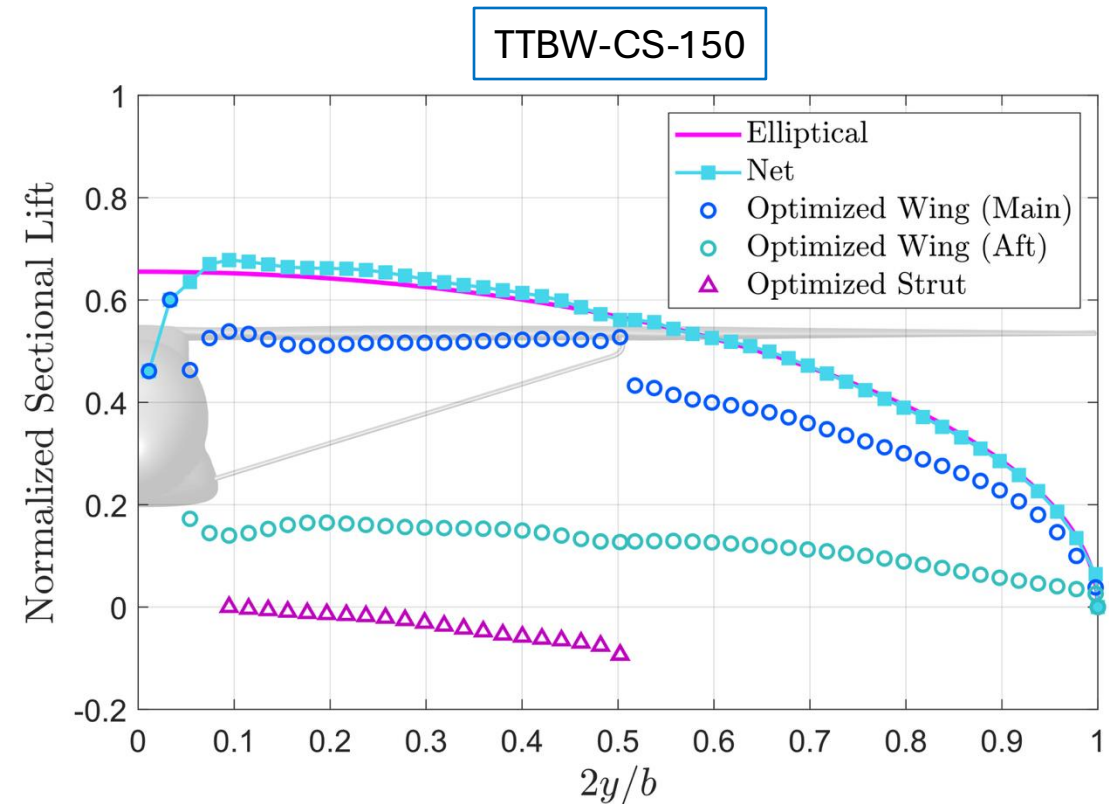
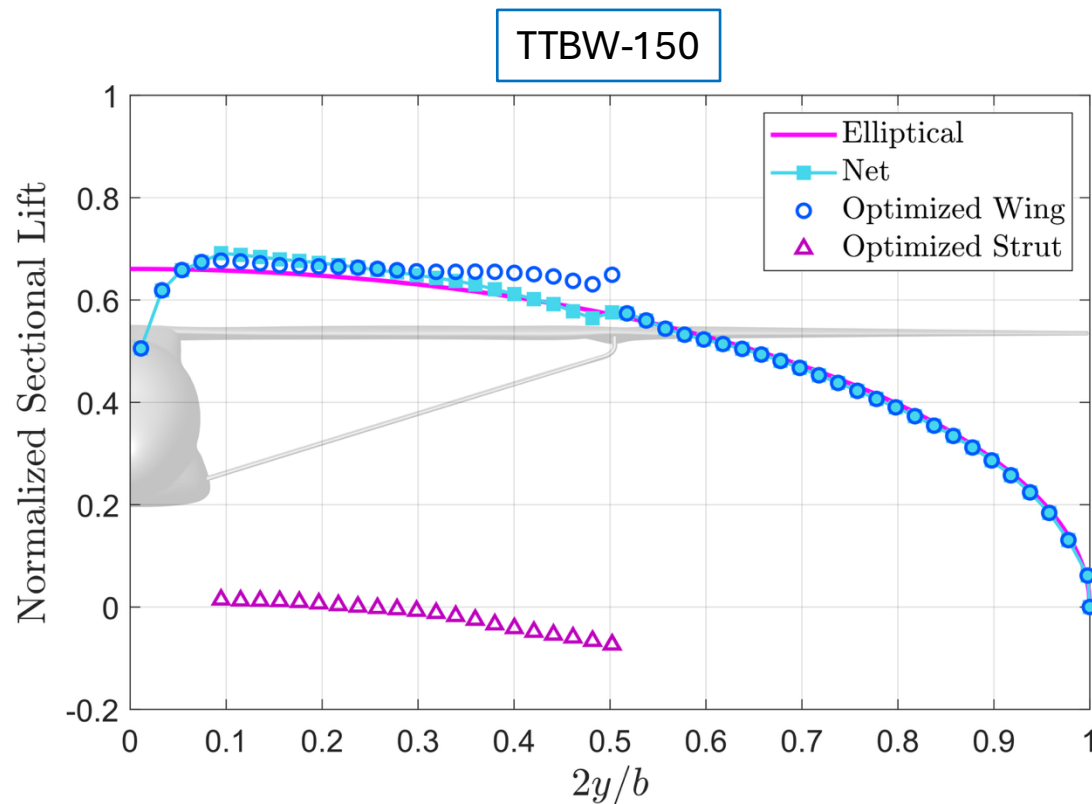
Surface pressure contours



Airfoil profiles and pressure distributions

Optimization again mitigates shock formation around the wing-strut junction. Optimized pressure distributions demonstrate that the cruise-slotted wing can sustain higher aft loading, which would normally lead to boundary-layer separation.

Optimized Spanwise Lift Distributions

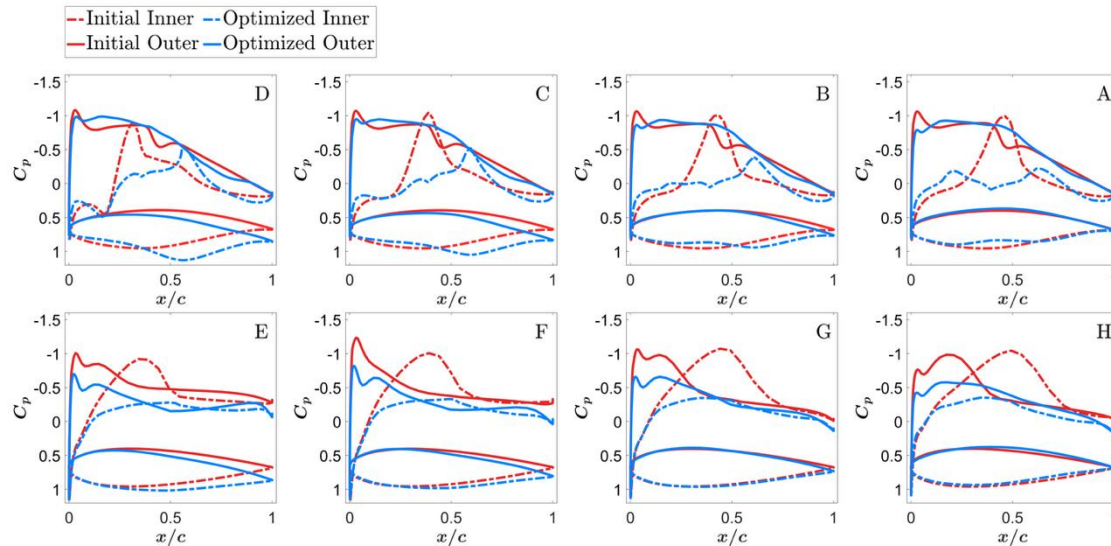
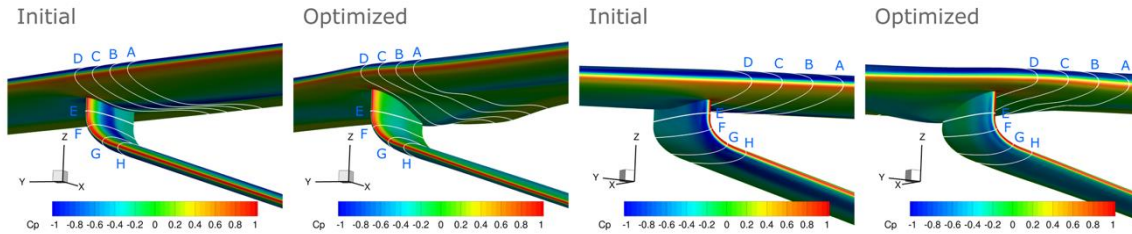


- **TTBW-150:** Wing distribution shifted positively near wing-strut junction to counteract negative strut lift required to alleviate transonic channel effect¹⁻³
- **TTBW-CS-150:** Similar shift occurs but only over the main element since aft element load is weakly sensitive to changes in local effective angle of attack⁴

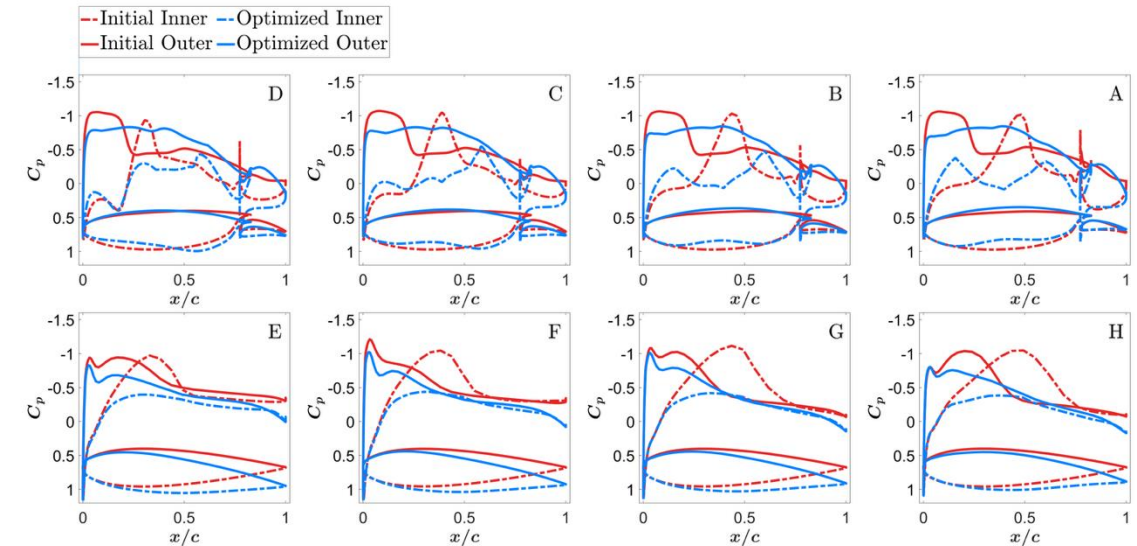
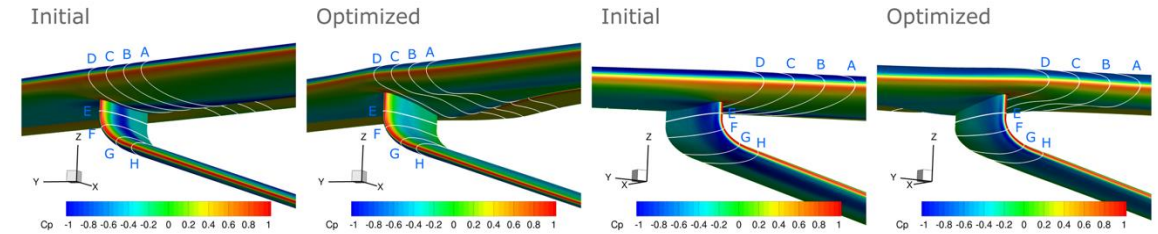
Wing-Strut Junction Airfoils and Pressure Distributions



TTBW-150



TTBW-CS-150



Both configurations feature an outwards force distribution to mitigate shock formation and boundary-layer separation within the wing-strut junction.

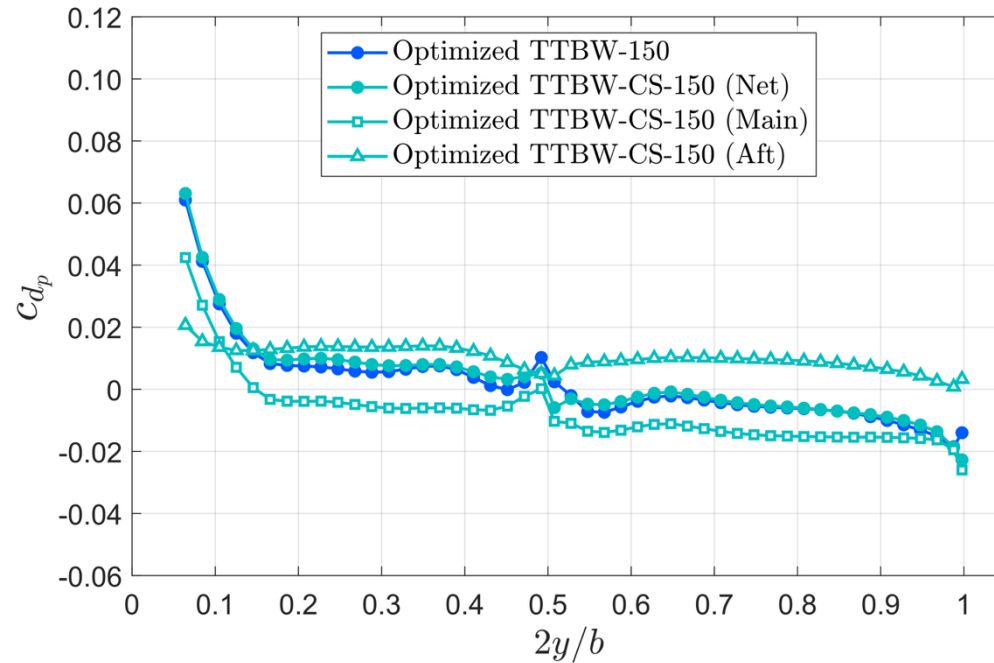
Optimized On-Design Cruise Performance



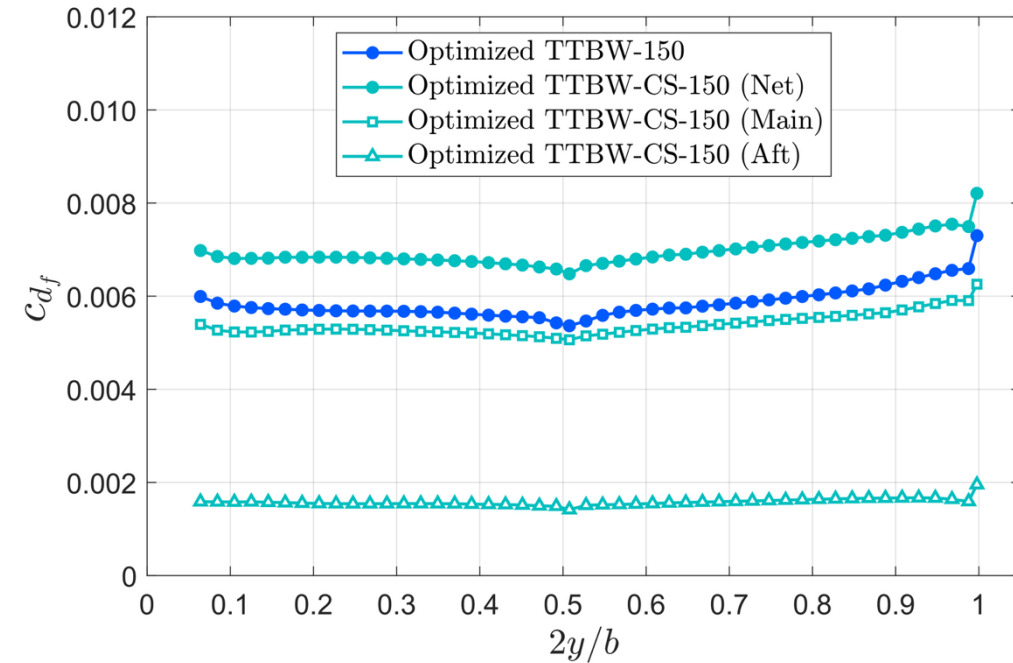
Parameter	TTBW-150	TTBW-CS-150	Delta
Lift coefficient, C_L	0.560	0.560	+0.0%
Drag coefficient, C_D	0.0216	0.0223	+3.0%
Pressure drag coefficient, C_{Dp}	0.0097	0.0094	-2.6%
Skin-friction drag coefficient, C_{Df}	0.0119	0.0128	+7.6%
Lift-to-drag ratio, L/D	25.9	25.2	-3.0%
Aero. range efficiency, $M(L/D)$	20.7	20.2	-3.0%

The cruise-slotted TTBW experiences 3% more on-design drag than the non-slotted TTBW due to increased skin-friction drag.

Optimized Pressure and Skin-Friction Drag Distributions



Spanwise pressure drag coefficient distributions.

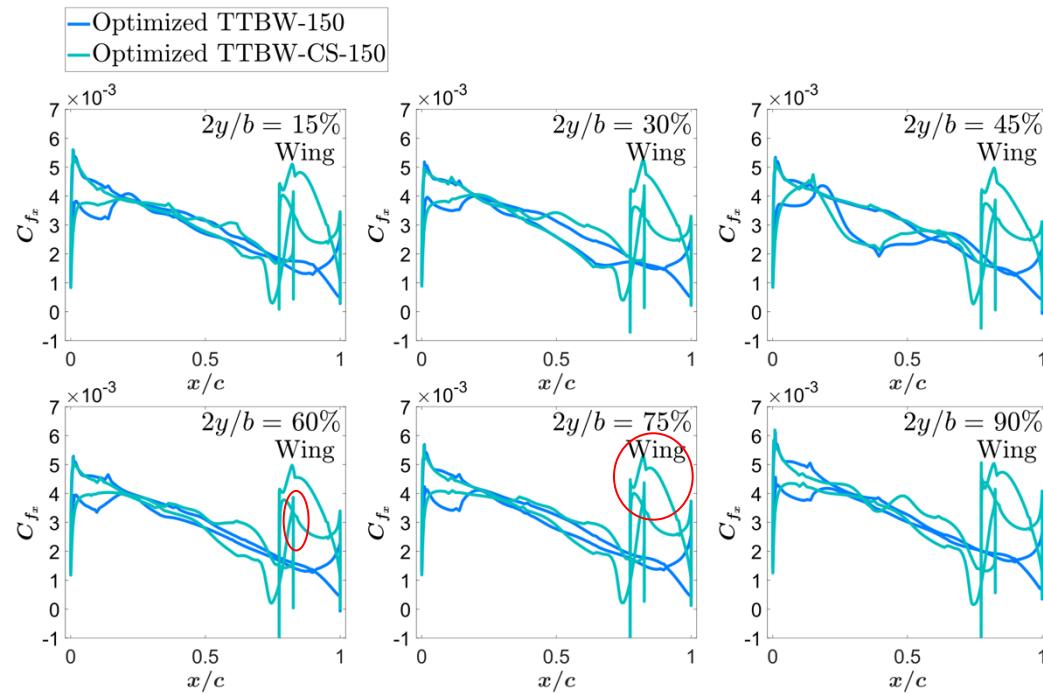


Spanwise skin-friction drag coefficient distributions.

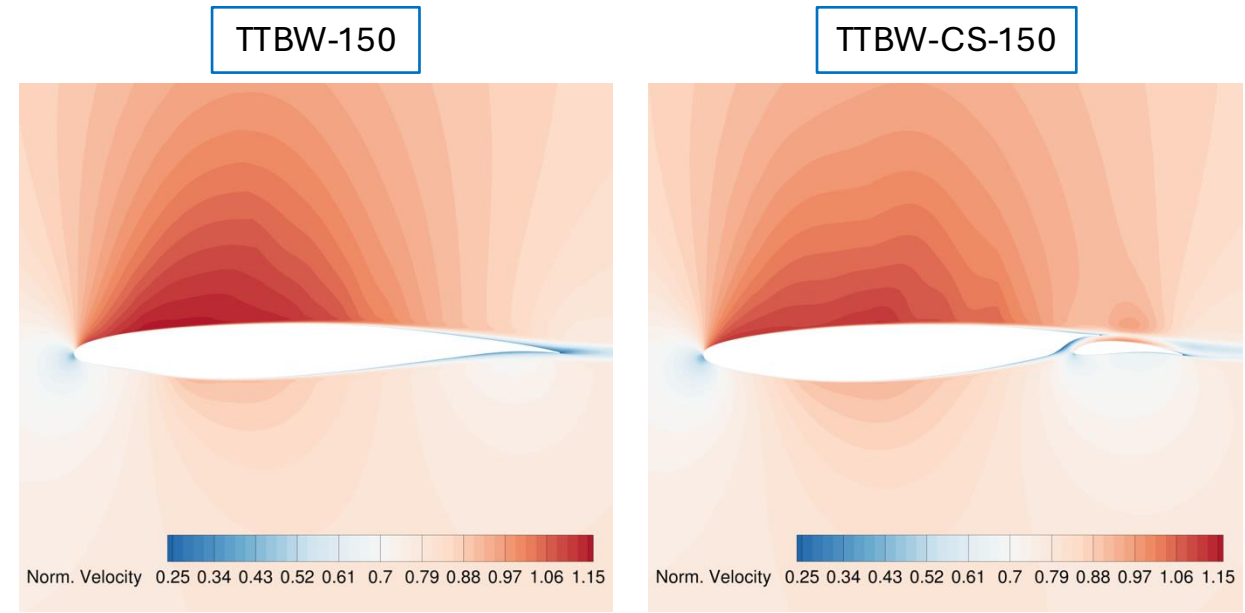
- The optimized TTBW-150 and TTBW-CS-150 designs experience **similar pressure drag across each wing**, consistent with the findings of Hiller et al. 2024¹
- The **cruise-slotted wing experiences much more skin-friction drag**
 - 18% higher average wing C_{df}
 - Average main element C_{df} makes up 91% of average non-slotted wing C_{df}

¹Hiller et al., *AIAA SciTech Forum*, 2024. doi: 10.2514/6.2024-0677

A Closer Look at Skin-Friction Drag



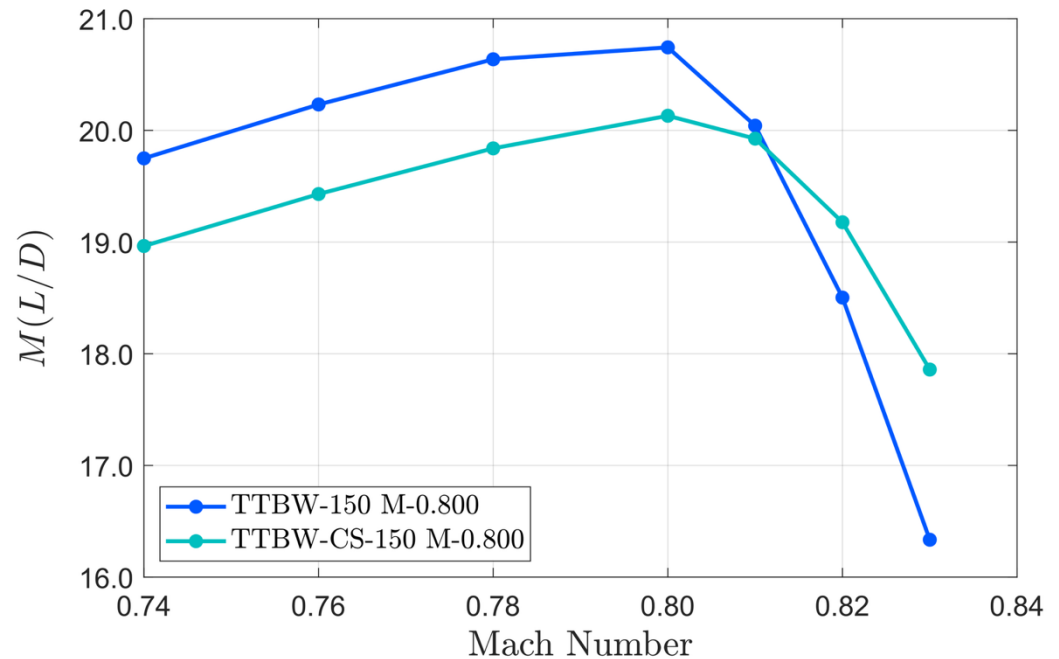
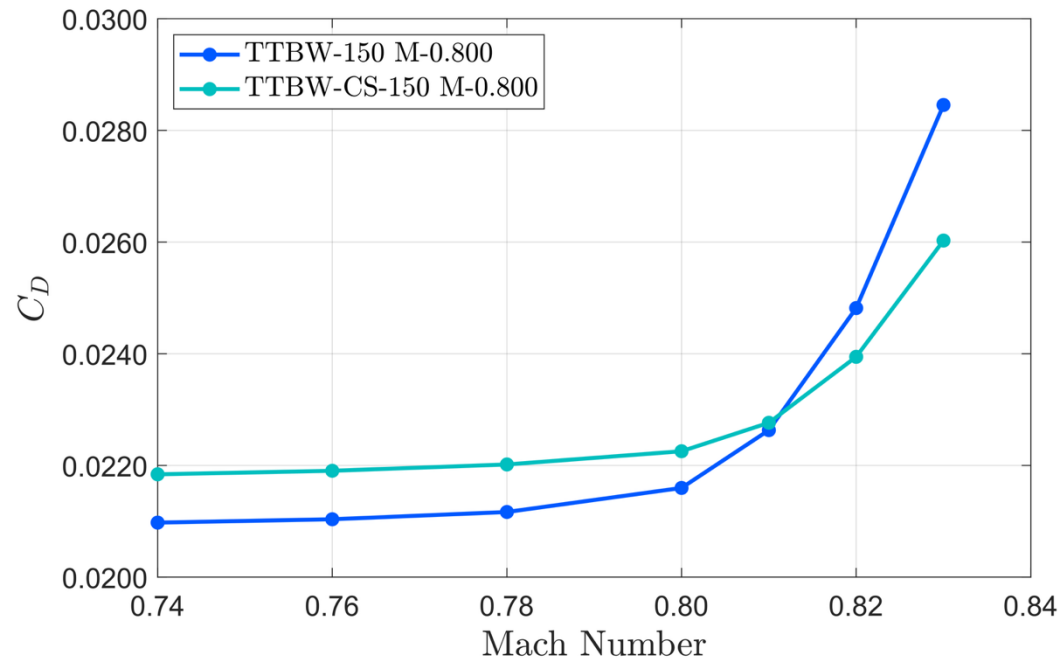
Skin-friction drag coefficient distributions.



Velocity magnitude contours (normalized by free-stream velocity) at 15% semispan.

- The **cruise-slotted wing** experiences **higher skin-friction drag coefficients** near the slot on the main and aft elements
 - **Accelerated slot flow** on main element (lower surface, TE) and aft element (upper surface, LE)
 - **Second, newly-formed boundary layer** on aft element

Off-Design Aerodynamic Performance



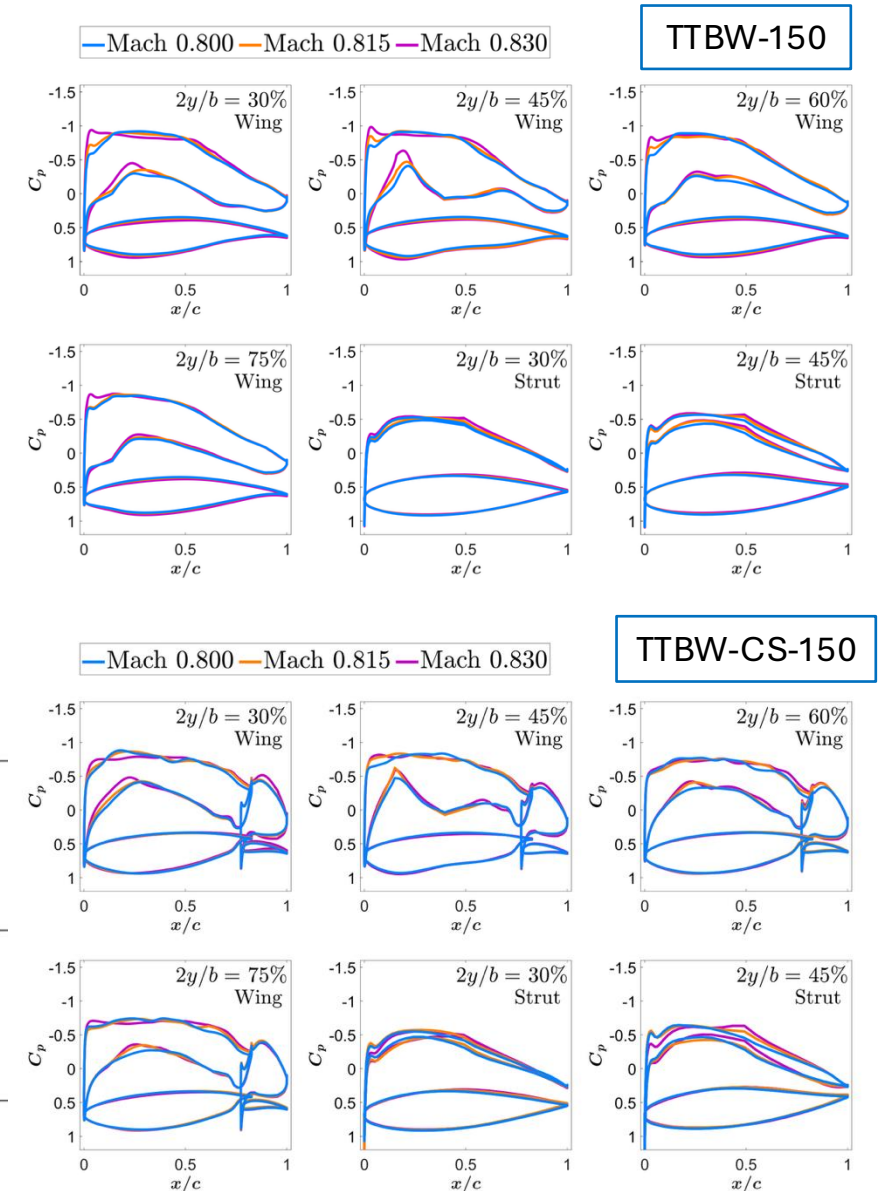
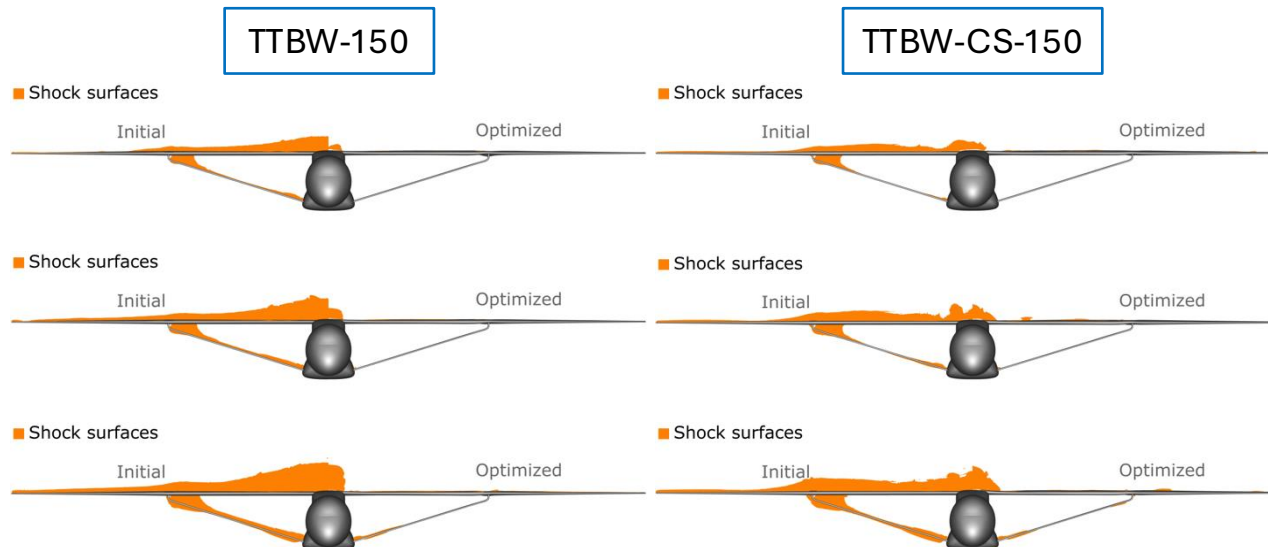
Cruise-slotted TTBW experiences more drag than the non-slotted TTBW below Mach ~0.800 but has the advantage of a **more gradual drag rise**. However, the maximum $M(L/D)$ remains far below that of the non-slotted variant.

Mach Number Sensitivity Studies



Hypothesis: The on-design aerodynamic advantage of the cruise-slotted wing will manifest if both configurations are forced to trade against wave drag, which is often present in practical aircraft designs.

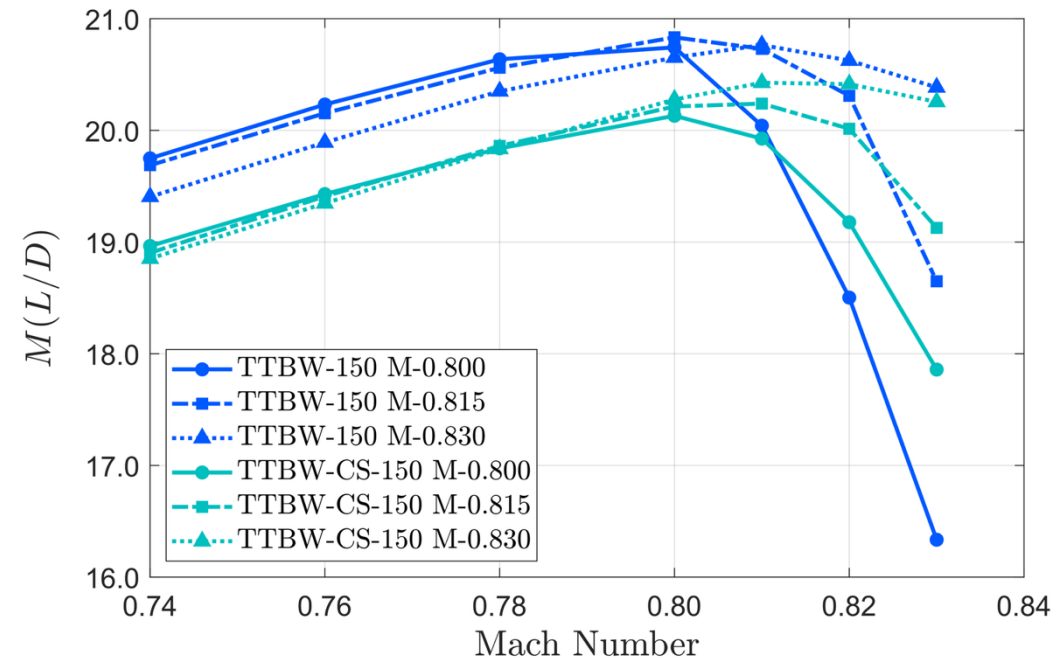
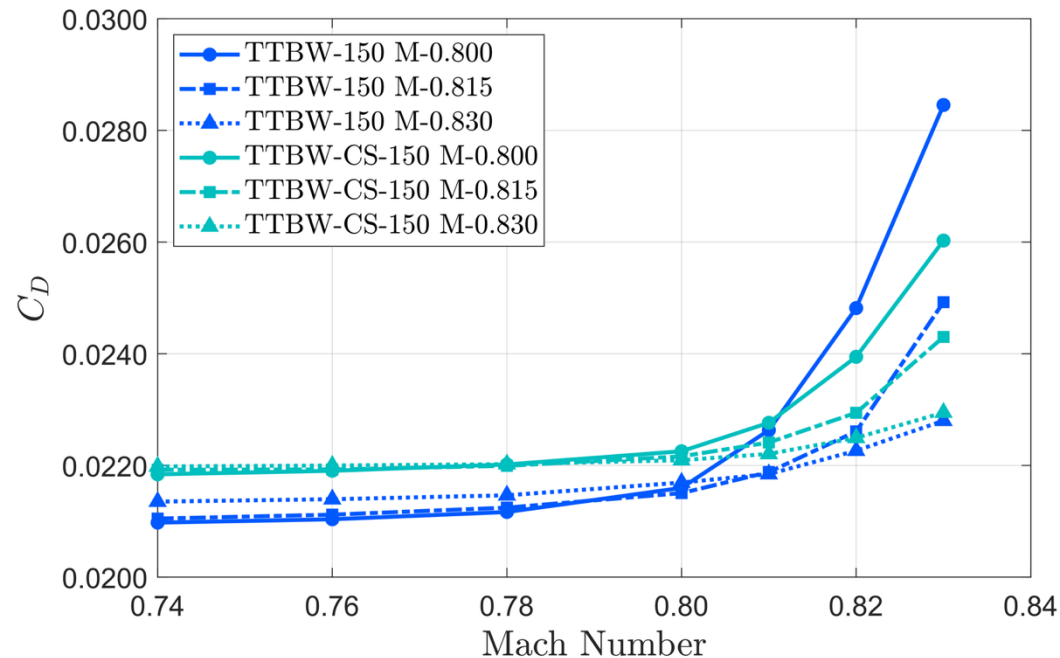
- TTBW-150 and TTBW-CS-150 are re-optimized at Mach 0.815 and 0.830 to push the envelope
- Single-point optimization is unexpectedly successful in maintaining a low wave drag design at all Mach numbers



Drag Rise and Aerodynamic Range Efficiency Curves



Note: Mach number increases from solid to dashed to dotted lines.



Cruise-slotted TTBW experiences a **more gradual drag rise** than the non-slotted TTBW for all single-point optimized designs. However, the **maximum $M(L/D)$ remains lower** for the cruise-slotted TTBW, even at higher cruise Mach numbers, due to the very low wave drag of all optimized configurations.

Summary and Conclusions



- Demonstrated that an aerodynamically efficient single-aisle cruise-slotted truss-braced wing (TTBW) design can be achieved at Mach 0.80—with the mitigation of shock formation within the wing-strut junction—through aerodynamic shape optimization based on the RANS equations
- Identified strikingly similar optimized features between the cruise-slotted and non-slotted TTBW configurations:
 - A negatively lifting strut near the wing-strut junction, locally offset by lift from the wing/wing's main element
 - Novel insets and bumps that mitigate pressure peaks from the transonic channel effect
 - Outwards force distribution in the wing-strut junction region
- The cruise-slotted TTBW experiences 3.0% more cruise drag than the non-slotted TTBW at the design point due to increased skin-friction drag, but benefits from a more gradual drag rise as the Mach number is increased
- However, the cruise-slotted TTBW does not achieve a higher maximum $M(L/D)$ compared to the non-slotted TTBW, owing to both configurations' low wave drag; this gap persists but lessens when the configurations are optimized for higher design Mach numbers

Recommendations for Future Work



For Turbulent Designs of the Cruise-Slotted TTBW:

- Perform [multipoint optimization](#) in order to obtain more practical designs that demonstrate the benefit the slotted airfoils' ability to reduce wave drag and drag from shock-induced flow separation
- Include the impact of trim drag through a [pitching moment constraint](#)
- Use a [finer geometric parameterization of the slot](#) to control its shape

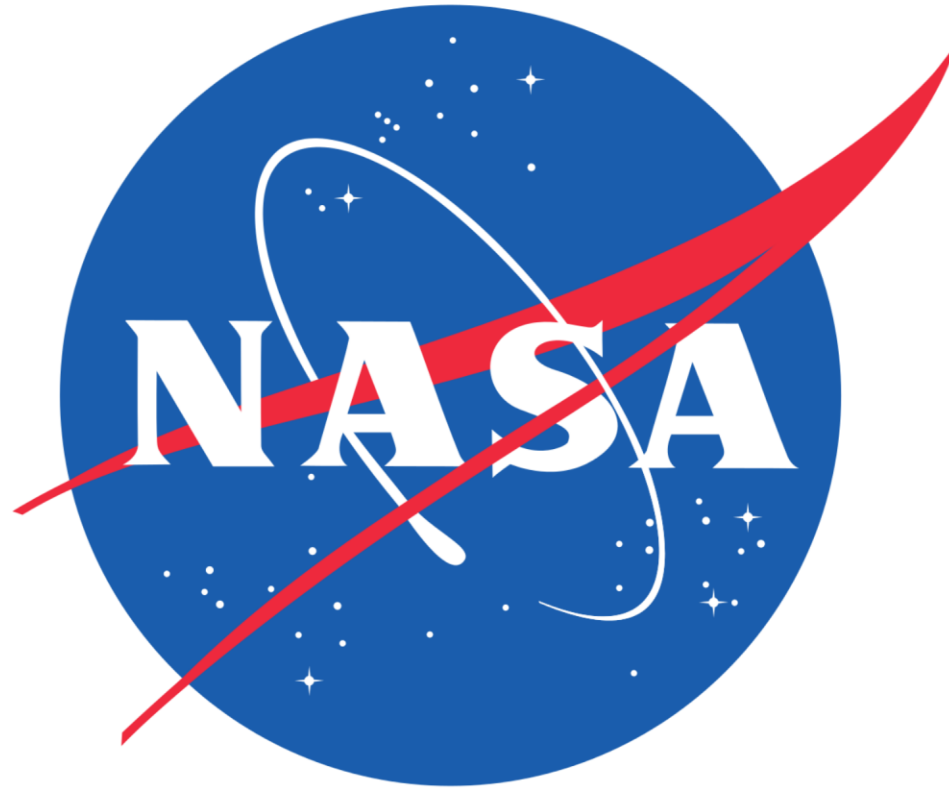
For Natural Laminar Flow Designs of the Cruise-Slotted TTBW:

- Include [transition prediction](#) in the optimizations to enable laminar flow over the main and aft elements for overcoming the skin-friction drag penalties of turbulent designs

Acknowledgments



- Funding for this work was provided by the **NASA Advanced Air Transport Technology (AATT) project**
- Computational resources provided by the NASA High-End Computing Capability (HECC) program through the **NASA Advanced Supercomputing (NAS) Division** at Ames Research Center
- NASA AATT technical managers: William E. Milholen and Sally A. Viken
- Professor David W. Zingg (University of Toronto) for providing access to the Jetstream aerodynamic shape optimization framework
- Several past and present LAVA team members:
 - Cetin C. Kiris, Ercan Dumlupinar, and Elisha V. Makarevich
 - Jeffrey A. Housman, David A. Craig-Penner, and Brandon M. Lowe
- Appreciation extended to Brandon Lowe and Josh Anibal for internal review



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